DEVELOPMENT OF A SIMULATED HIGH-TEMPERATURE NUCLEAR LOOP

By J. P. McGee, N. H. Coates, and G. E. Fasching

* * * * * * * * * * * information circular 7981

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
Fred A. Seaton, Secretary

BUREAU OF MINES
Marling J. Ankeny, Director

The work upon which this report is based was done under a cooperative agreement between the Bureau of Mines, U.S. Department of the Interior, and the U.S. Atomic Energy Commission.

This publication has been cataloged as follows:

McGee, James Paul.

Development of a simulated high-temperature nuclear loop, by J. P. McGee, N. H. Coates, and G. E. Fasching. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1960]

17 p. illus. 26 cm. (U.S. Bureau of Mines. Information circular 7981)

Based on work done under a cooperative agreement between the Bureau of Mines and the U.S. Atomic Energy Commission.

1. Heat - Transmission. I. Title. II. Title: Nuclear loop. (Series)

TN23.U71 no. 7981 622.06173

U.S. Dept. of the Int. Library.

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25 D.C. Price 20 cents

CONTENTS

Page

Summary.. 1
Introduction... 1
Acknowledgments.. 3
Description of the loop.................................. 3
    Induction-heated simulated nuclear reactor (ISR)..... 3
    Helium-to-air heat exchanger......................... 5
    Helium-recycle compressor............................ 7
    Valves... 8
    Dust filter.. 8
    Piping and fittings.................................. 9
Equipment performance.................................... 9
    Induction-heated simulated nuclear reactor (ISR)..... 9
        30-inch, 300-p.s.i.g. flanged joint.............. 9
        Rupture-disk failure............................. 9
        Refractory deterioration......................... 9
    Helium-to-air heat exchanger......................... 10
    Helium-recycle compressor............................ 11
    Helium-purification system........................... 14
    Valves and flanges................................... 15
    Helium leakage....................................... 15
Conclusions.. 16

ILLUSTRATIONS

Fig.

1. 2,500° F., 250-p.s.i.g. helium-recycle loop.......... 4
2. Flowsheet for induction-heated simulated nuclear reactor system.. 5
3. 250-p.s.i.g. induction-heated simulated nuclear reactor (ISR).. 6
4. Helium-to-air heat exchanger.......................... 7
5. Recycle compressor for high-temperature helium....... 8
6. Tube bundle removed from ISR helium-air heat exchanger.. 12
7. Helium-to-water, helium-to-air heat exchanger........ 12
8. Recycle compressor for helium at 1,000° F. and 250 p.s.i.g... 12
9. Front view of impeller from helium-recycle compressor, showing damage to blades................ 13
10. Helium-purification system for induction-heated simulated nuclear reactor.......................... 15
11. Bellows-seal valve for helium at 300 p.s.i.g. and 1,000° F.. 16

DEVELOPMENT OF A SIMULATED HIGH-TEMPERATURE NUCLEAR LOOP[1]

by

J. P. McGee,[2] N. H. Coates,[3] and G. E. Fasching[4]

SUMMARY

As part of a joint U.S. Atomic Energy Commission-Federal Bureau of Mines program for using nuclear energy to supply process heat, a simulated nuclear loop has been constructed to test components. This loop has been operated for more than 1,800 hours at 100 p.s.i.g. Of this period, 23 hours were at 2,500° F. and higher; 540 at 2,000° to 2,500° F.; 840 at 1,500° to 2,000° F.; 200 at 1,000° to 1,500° F.; and 260 below 1,000° F. Leakage at flanges and welds was not a serious problem. A helium-recycle system with gas temperatures of 2,300° to 2,500° F. and a static pressure of 250 p.s.i.g. appears feasible.

Difficulties were encountered with the recycle compressor due to thermal distortion of the impeller and shaft. The use of sealed bearings limits compressor operation to the life of the bearings.

A leak developed in the tube sheet of the helium-to-air heat exchanger. Further development is necessary before shell and tube exchangers can be used for high-temperature, nuclear process-heat transfer.

Contamination of the recycled helium by occluded gases, principally water vapor, resulted in loss of carbon from the graphite fuel elements. Therefore, a 1-percent side stream of the helium was passed through a purification system with two freon condensers in series. Carbon loss was reduced enough to allow continuous operation for relatively long periods.

INTRODUCTION

The Federal Bureau of Mines has developed a continuous pressure process for producing a synthesis gas, consisting essentially of carbon monoxide and hydrogen, directly from coal, steam, and oxygen. Actually, coal and steam furnish the necessary chemical elements, carbon and hydrogen, which appear in the product gas, but oxygen is provided for the combustion of additional coal to supply heat for the endothermic steam-coal reaction. However, the cost of compressed oxygen and the additional coal makes the gasification process uneconomical at present, so cheaper heat must be obtained if synthesis gas via coal gasification is to be competitive with other processes.

---

[1] Work on manuscript completed February 1960.

[2] Special assistant to the chief, Branch of Coal Gasification, Division of Solid Fuels Technology, Bureau of Mines, Morgantown, W. Va.

[3] Chemical engineer, Bureau of Mines, Morgantown, W. Va.

[4] Electrical engineer, Bureau of Mines, Morgantown, W. Va.

One potential source for the energy required is heat from nuclear fission Although most efforts for peacetime use of atomic energy have been directed to propulsion and the production of electric power, the use of nuclear energy as a source of heat, not only for gasification, but for other chemical processes, has several advantages. First, higher operating temperatures are possible. Temperatures are limited primarily by materials of construction; there is no inherent limitation as there is in the combustion of hydrocarbon fuels. Second, as the unused heat is returned to the reactor, there are no stack losses, and more efficient heat utilization is obtainable. Third--and most important of all from the standpoint of coal gasification--heat is generated without air, oxygen, or compression costs.

As part of a joint Atomic Energy Commission-Bureau of Mines investigation of the application of heat from nuclear fission to chemical processing, a simulated nuclear system has been designed and constructed in which heat is produced by electric induction to circumvent the complications of radioactivity. Heat, generated within a bed of graphite spheres that simulate nuclear fuel elements, is transferred to a pressurized stream of recycled helium that in an external heat exchanger can heat chemical process streams to 2,000° F. Having demonstrated the feasibility of gasifying subbituminous coals and lignite at about 1,800° F. in alloy-steel tube-coil gasifiers,[5] the Bureau envisions the heat exchanger in this system as a "nuclear-energy" gasifier. For low-rank coals the operating temperature of the gasifier need not exceed 1,800° F., but higher temperatures obtainable in a nuclear process-heat reactor would materially aid the process.

Because virtually no information was available on high-temperature helium recycle systems such as the nuclear system envisioned, the induction-heated prototype was designed and constructed to operate at a maximum temperature and pressure of 2,500° F. and 250 p.s.i.g. Electric induction heating is attractive because it most nearly simulates the type of heating provided by nuclear fuel elements, permits more freedom in the fuel-element geometry, and eliminates potentially troublesome electrode connections required for electric-resistance heating.

Because the energy required to circulate an equal weight of hot helium through piping and equipment decreases rapidly with increase in pressure of the helium, the proposed nuclear process is particularly well adapted to pressure-gasification processes. Most synthesis processes require feed gases at pressures of 20 atmospheres or above; when gases are generated at that pressure there is a saving in compression costs. The major causes of alloy failur at high temperatures--stress and oxidation--are reduced to a minimum by balancing the pressure of the unreactive helium on one side of the metal tubes with the pressure of the reducing gases and steam in the gasification zone on the other side.

---

[5] Bureau of Mines, Annual Report of the Secretary of the Interior for 1955: Rept. of Investigations 5236, July 1956, p. 29.

Objectives of the design and construction of the prototype unit are twofold:

1. To divulge and solve the engineering problems relative to the design, construction, and operation of the system--particularly those relating to heat transfer and fluid mechanics of high-temperature helium--and apply this information to the development of nuclear process-heat technology;

2. To obtain information for the design, construction, and operation of a coal gasifier (heat exchanger) that can transfer fission-derived heat to a steam-coal mixture with essentially no radioactivity imparted to the product gas.

ACKNOWLEDGMENTS

This investigation is being conducted by the Federal Bureau of Mines, Morgantown, W. Va., as part of a cooperative agreement with the U.S. Atomic Energy Commission. The authors gratefully acknowledge the financial support of the Atomic Energy Commission and the assistance of S. G. Nordlinger of that agency.

DESCRIPTION OF THE LOOP

Figure 1 shows the loop as originally constructed. The heat-transfer fluid, helium, is heated to 2,300° to 2,500° F. in the induction-heated simulated nuclear reactor (ISR), shown in figure 1 as "simulated reactor." The helium is cooled to 1,000° F. in a heat exchanger, filtered to remove particles that could damage a high-speed compressor, and recycled to the ISR.

As indicated in figure 2, the system consists of two circuits--one for air and one for helium. In the air circuit, air is recycled through the tubes of a shell-and-tube neat exchanger to cool the helium outside the tubes. Standard equipment is used, including a reciprocating-type recycle compressor, an air precooler, and an electric preheater for controlling inlet temperatures to the heat exchanger.

The helium circuit includes the ISR, a helium-to-air heat exchanger, a dust filter, and a recycle compressor. These development items are described in detail in the following sections.

Induction-Heated Simulated Nuclear Reactor (ISR)

The ISR, shown in figure 3, is a type 304 stainless steel pressure vessel designed for 300 p.s.i.g., with an operating pressure of 250 p.s.i.g. An induction coil heats a 6-inch-i.d. by 24-inch-high bed of graphite spheres, which in turn transfers the heat to the recycled helium. Two ceramic tubes

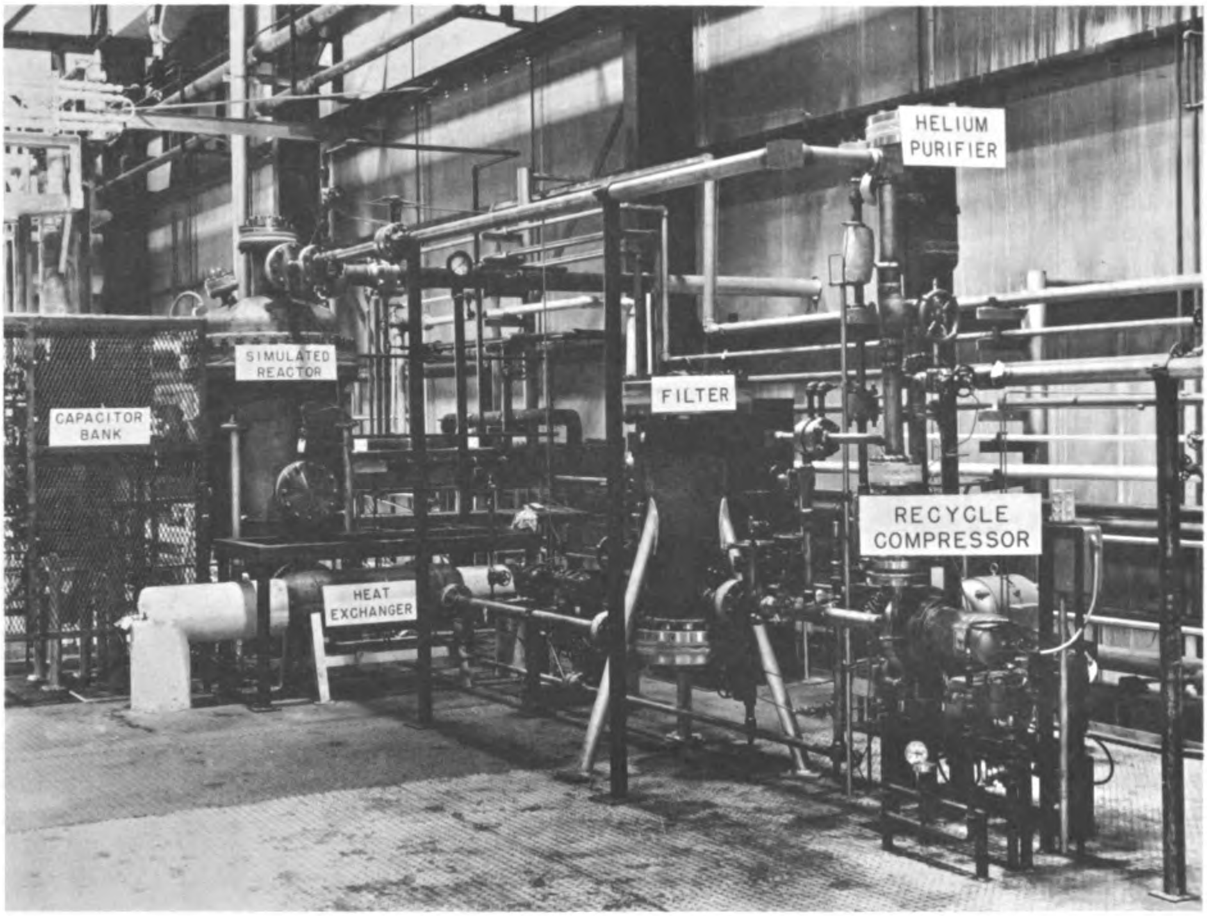

FIGURE 1. - 2,500° F., 250-p.s.i.g. Helium-Recycle Loop.

and a layer of granular insulation between the graphite spheres and induction coil minimize heat losses. Helium enters the top of the vessel at 1,000° F., flows downward over the graphite elements, and leaves the reactor at 2,500° F. through a refractory-lined pipe to the heat exchanger.

Auxiliary heating coils in the graphite and refractory insulation help drive occluded gases and moisture from the system while it is being evacuated initially.

Energy for the induction field is furnished by a 9,600-cycle-per-second, 100-kw. induction generator.

The exit-gas temperature is measured by a high-velocity thermocouple; shielded couples are positioned throughout the reactor for controlling the operation.

All connections to the ISR are the flange type with octagonal ring-joint seals.

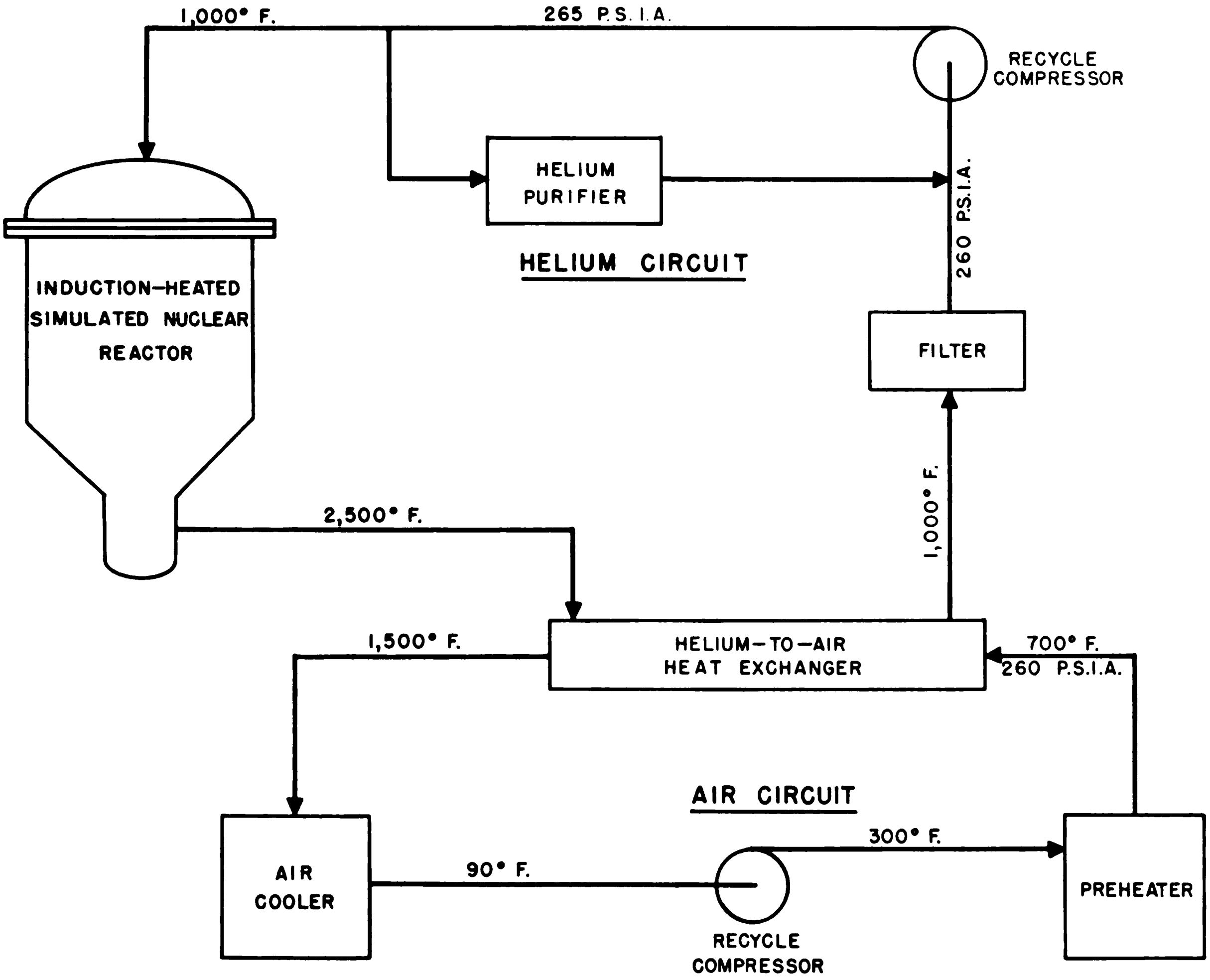

FIGURE 2. • Flowsheet for Induction-Heated Simulated Nuclear Reactor System.

Helium-To-Air Heat Exchanger

Serving as the heat sink for the system, and as a prototype for a high-temperature, alloy-steel, gas-to-gas heat exchanger, the unit shown in figure 4 cools the recycled helium from 2,500° to 1,000° F. Shell-and-tube construction is used, with helium flowing outside the tubes and air circulating through the tubes. Heat load on the exchanger is 100,000 B.t.u./hr.

Pressure of air on the tube side is balanced by the pressure of the helium on the shell side, and mass flows of air are chosen so that the tube-wall temperature will not exceed 1,800° F. The tubes are type 310 stainless steel, one of the best commercially available high-temperature and oxidation-resistant materials for which welding techniques are fully developed. Alloys currently being developed may permit operation at several hundred degrees above the temperature allowable for type 310 stainless steel; when manufacturers gain more experience in fabricating these materials they will be tested for suitability in heat exchangers.

Original from THE OHIO STATE UNIVERSITY

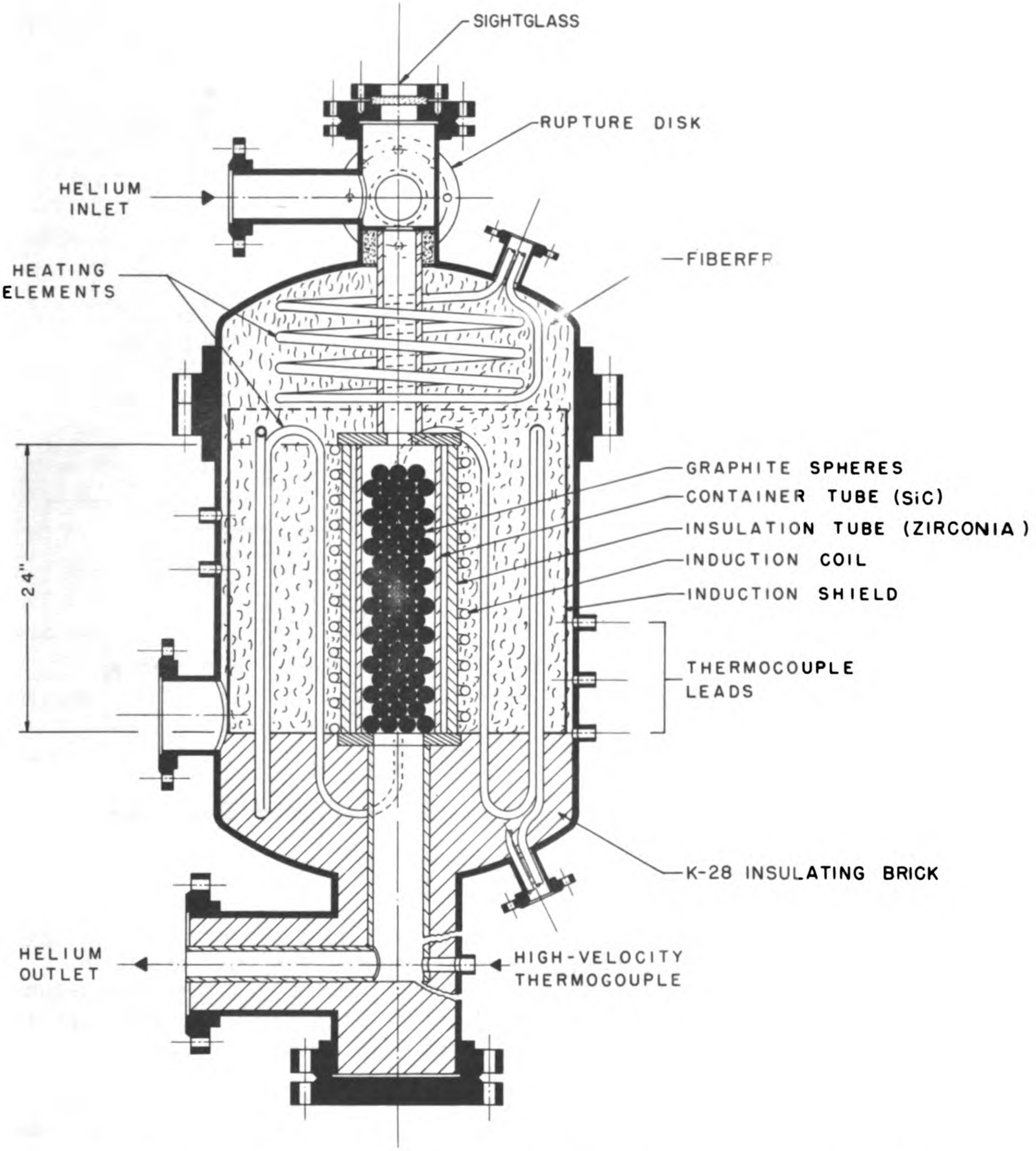

FIGURE 3. - 250-p.s.i.g. Induction-Heated Simulated Nuclear Reactor (ISR).

During initial tests with the ISR system, a low helium velocity was maintained to minimize the pressure drop across the exchanger until operating experience was gained with the centrifugal recycle compressor. Mass flow, "G," of helium through the exchanger is approximately 1,000 lb./(ft.^{2})(hr.), and mass flow of air is about 29,000 lb./hr.-ft.^{2}. Total heating surface

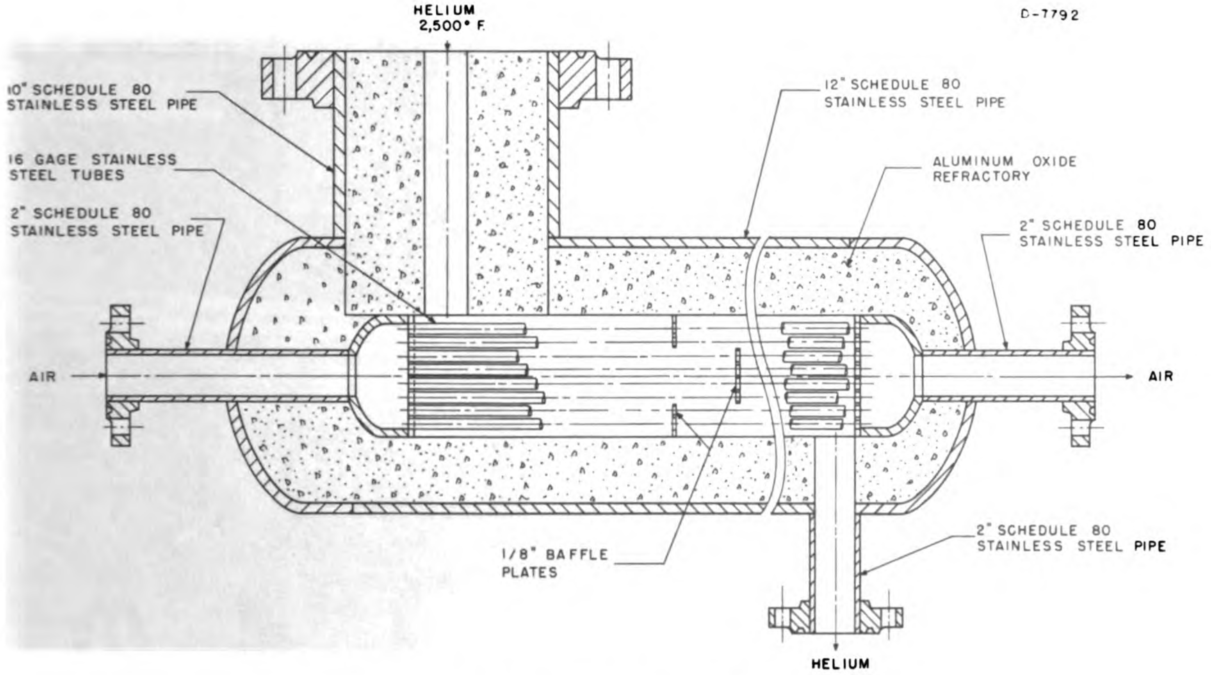

FIGURE 4. - Helium-to-Air Heat Exchanger.

based on the outside diameter of the tubes is 12.6 sq.ft., and the overall heat-transfer coefficient, "U," is approximately 14 B.t.u./(hr.)(ft.^{2})(° F.).

Helium-Recycle Compressor

Illustrated in figure 5, the helium-recycle compressor is a single-stage centrifugal type consisting of an overhung impeller, diffuser, and drive motor. The entire assembly is hermetically sealed--a construction often referred to as "canning."

The drive is a 2-hp., 3-phase, 400-cycle induction motor. The 400-cycle current is obtained from a 5-kw. alternator driven by a 7.5-hp., 60-cycle induction motor. Compressor speed is regulated by changing the size of the pulley on the V-belts on the motor-alternator set.

The compressor is designed to raise the pressure of 1,000° F. helium from 260 to 265 p.s.i.g., which corresponds to an adiabatic head of approximately 11,000 feet.

In a preliminary test at the Turbocraft plant, Pasadena, Calif., the compressor performed satisfactorily with air (at atmospheric pressure) instead of helium; a head of 11,000 feet was developed at a speed of 21,000 r.p.m. Maximum allowable speed is 23,000 r.p.m.

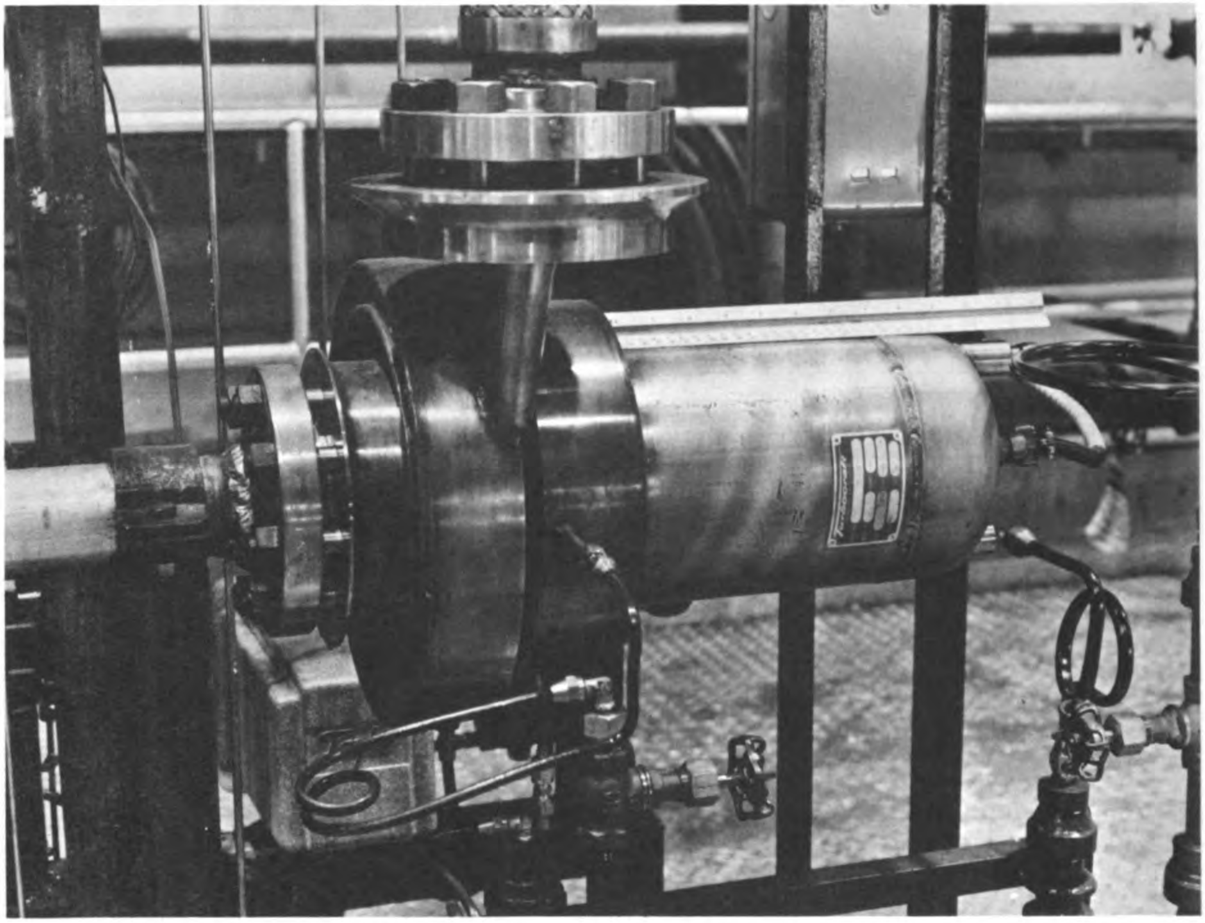

FIGURE 5. - Recycle Compressor for High-Temperature Helium.

Valves

All valves in the system are type 304 stainless steel with leakproof stems. The larger 1- and 2-inch valves are of the bellows-seal type, and the instrument valves are of the 1/4-inch diaphragm type.

Dust Filter

The filter protects the high-speed recycle compressor from damage by particles entrained in the helium and indicates the amount of erosion of the ceramic materials and graphite heating elements in the ISR. Constructed of type 304 stainless steel, and flanged at the top and bottom, the filter is 12 inches i.d. by 3 feet long. A rectangular filter element, Mine Safety Appliance No. 970-F Fiberglass, is placed longitudinally along the centerline of the vessel to give a 1- by 3-foot filter surface.

Piping and Fittings

All piping and fittings are schedule 80, type 304 stainless steel. Fittings, with octagonal ring-joint flanges, are designed for 2,000 p.s.i.g.

EQUIPMENT PERFORMANCE

Induction-Heated Simulated Nuclear Reactor (ISR)

30-Inch, 300-P.s.i.g. Flanged Joint

The top of the pressure vessel was constructed with ring-joint flanges for ease in assembling the internal components. These flanges were difficult to seal, however, and later it was discovered that they had not been bolted together during heat treatment. Efforts to make a perfect seal with carbon steel, type 304 stainless steel, and copper gaskets were unsuccessful, so the flanges were bolted together and sealed with a single-pass weld (using a 1/8-inch electrode).

Rupture-Disk Failure

The ISR pressure vessel was designed in accordance with specifications of the ASME Boiler and Pressure Vessel Code, Section VIII. These specifications permit use of either a safety valve or a rupture disk, but the latter was installed to eliminate helium leakage and avoid potential troubles in reseating a safety valve.

When the safety disk ruptured prematurely during a pressure test, the rapid discharge of helium lifted the center core of the column of graphite spheres, driving several of the spheres through the rupture-disk nozzle at high velocity before eight of them jammed in the vertical throat at the top of the vessel. This demonstrated that such a severe pressure letdown cannot be tolerated in a gas-cooled nuclear reactor system.

The fact that the Code permits a safety valve downstream from a rupture disk provided a specified piping arrangement is made appeared to offer a solution to the problem of excessive buildup of pressure in a gas-cooled process-heat reactor system. Therefore, until a satisfactory safety valve could be procured, a restricting orifice was installed in series with the rupture disk to minimize the effect of a sudden letdown in pressure.

Refractory Deterioration

As the system accumulated hours of operation it became apparent that the insulation in the ISR was breaking down. The filter plugged several times with an accumulation of fine dust, a rubbery substance built up in the system, and on the several occasions when the loop was dismantled and the piping cleaned a considerable amount of fine dust was removed.

The insulating materials installed in the ISR consisted of K-28 insulating brick and Fiberfrax insulation with the following compositions:

	K-28	Fiberfrax
Al_2O_3	45.1	51.2
SiO_2	51.9	47.4
Fe_2O_3	1.3	-
TiO_2	1.4	-
B_2O_3	-	-
Na_2O	.2	.7
CaO	.1	-
MgO	Trace	-

An analysis of the material retained by the filter is:

	Percent
Al_2O_3	0.91
SiO_2	96.60
Fe_2O_3	.51
CaO	.41
MgO	1.10
Unknown	.47
Total	100.00

Helium-to-Air Heat Exchanger

After approximately 1,151 hours of operation a serious helium leak developed in the loop. All external connections tested leaktight, but helium was detected in the coolant air from the heat exchanger. When the tube bundle (fig. 6) was removed from the heat exchanger, it was observed that one tube had pulled loose from the weld to the tube sheet and that all tubes were distorted by thermal expansion. The type 310 stainless steel tubes were in excellent condition; although the outsides of the tubes were covered with a black deposit, there was no indication of corrosion.

This exchanger was replaced with a helium-to-water, helium-to-air exchanger having a minimum number of internal welds. Figure 7 shows the new exchanger.

Helium-Recycle Compressor

Initial difficulties with the recycle compressor (fig. 8) were attributed to a change in composition of the recycle gas. Water vapor from the insulation in the ISR and heat exchanger reacted with the graphite spheres to form carbon monoxide, which built up to 25 percent in the recycled gas, thus increasing the average molecular weight of the recycle gas from 4 to 10 and overloading the compressor motor. Lowering the pressure of the system temporarily to 50 p.s.i.g. reduced the motor current to rated level; after the concentration of carbon monoxide was reduced by purging, the pressure of the system was returned to 100 p.s.i.g.

The temperature of the helium was gradually increased, but when the temperature of the compressor reached 960° F. the compressor became noisy and was immediately shut down. When the machine was disassembled it was observed that the rotor had rubbed against the housing, probably owing to inadequate provision for thermal expansion (fig. 9). The clearance between the rotor and housing was increased from 0.030 to 0.035 inch, with no noticeable loss in efficiency. The compressor then operated at 1,000° F. for approximately 400 hours, but the machine again became noisy, so it was shut down and disassembled. Examination revealed the following:

1. The suction housing was slightly scored around the periphery (approximately 1 inch radially inward from the periphery);

2. All 12 disk blades were mildly scored at the tips (1/2 inch to 1 inch inward from the periphery);

3. The shaft was warped to a maximum runout of 0.047 inch;

4. The water-cooled copper seal was scored.

To correct these deficiencies, the following steps were taken:

1. The rotor shaft and disk were straightened;

2. The complete rotor assembly was statically and dynamically balanced;

3. The clearance of the water-cooled copper seal was increased to 0.028 inch;

4. The front clearance of the rotor disk was set at 0.056 inch and the rear clearance at 0.045 inch;

5. The bearing mounting at the compressor was realined with the impeller housing.

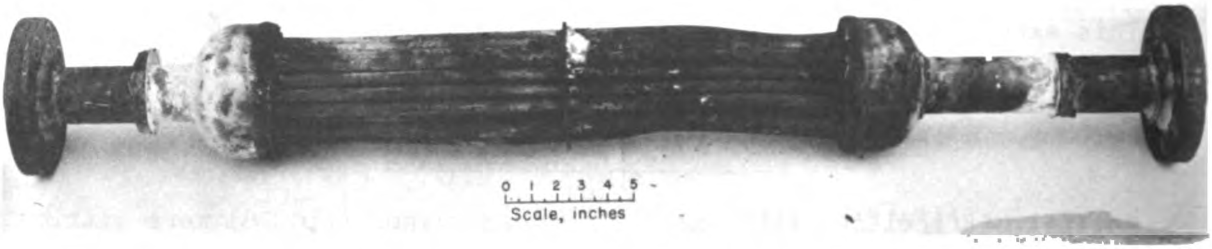

FIGURE 6. - Tube Bundle Removed From ISR Helium-Air Heat Exchanger.

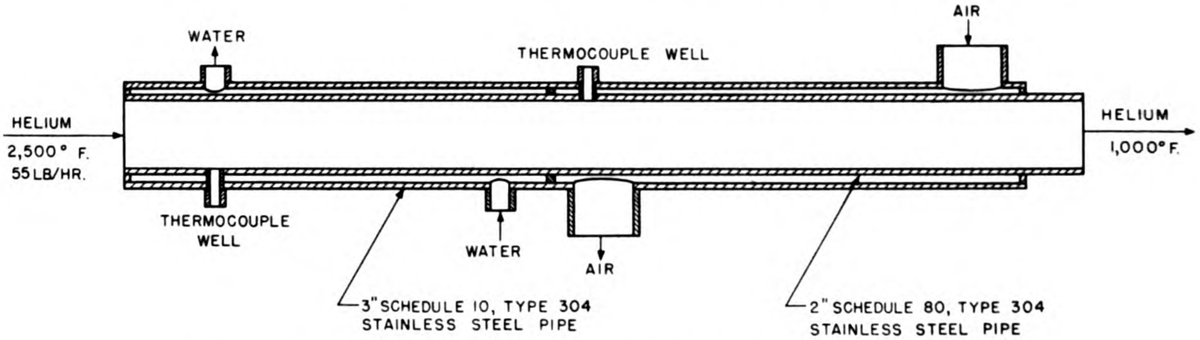

FIGURE 7. - Helium-to-Water, Helium-to-Air Heat Exchanger.

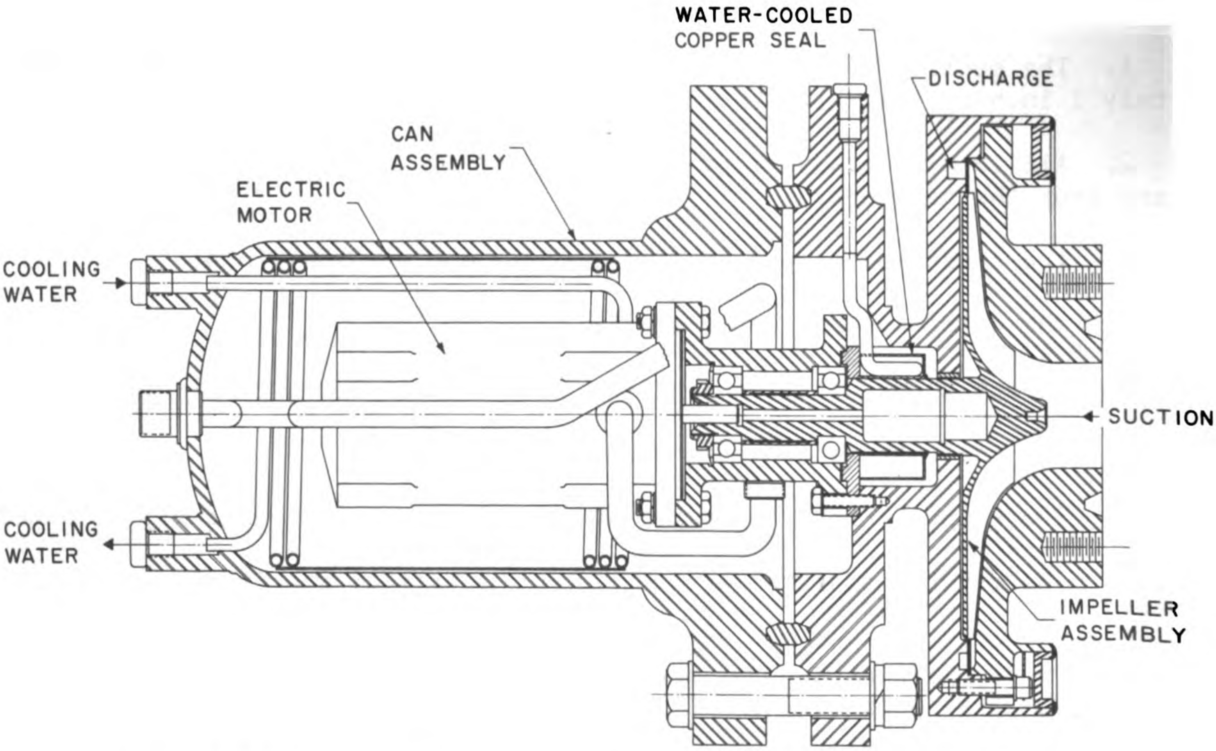

FIGURE 8. - Recycle Compressor for Helium at 1,000° F. and 250 p.s.i.g.

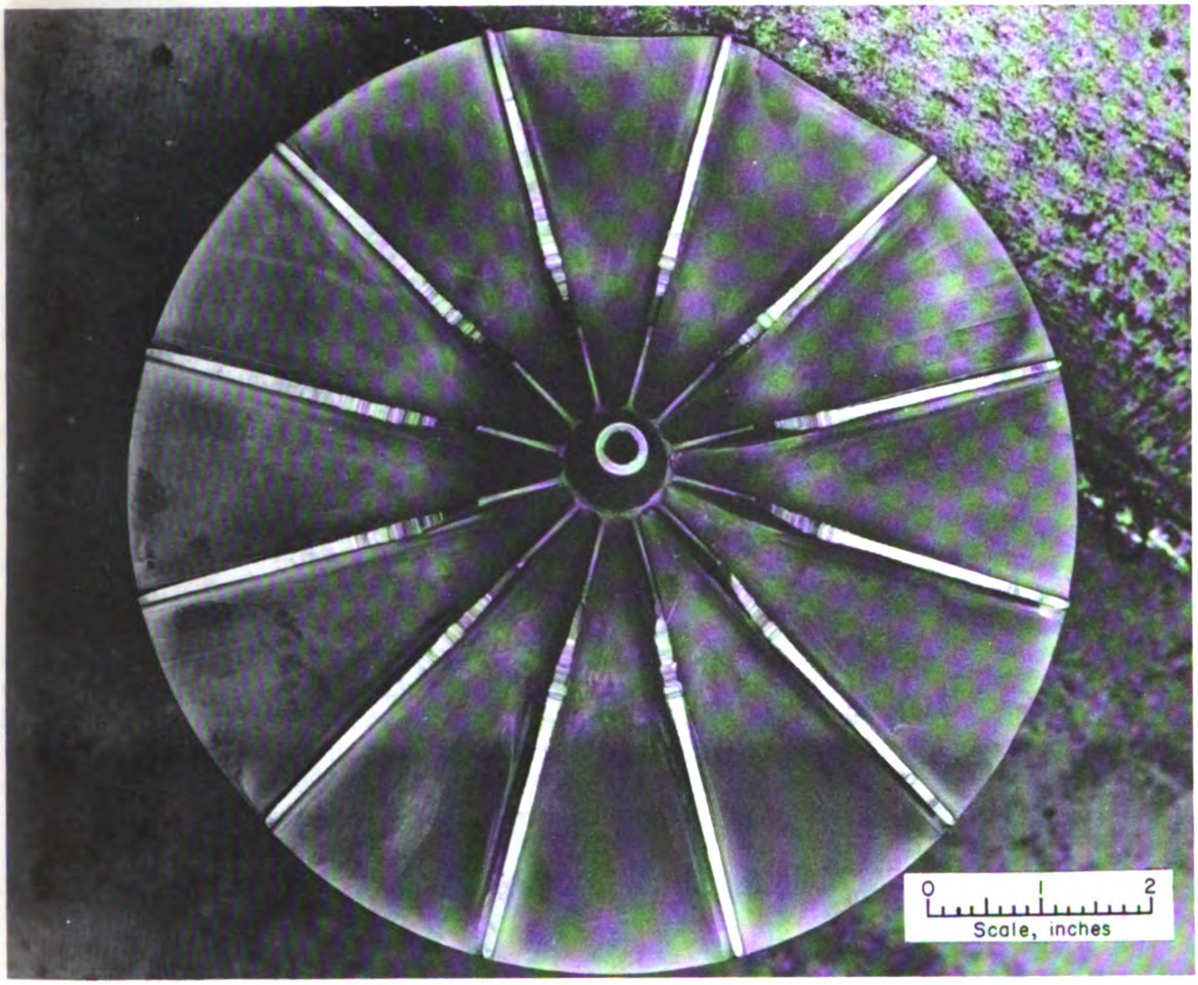

FIGURE 9. - Front View of Impeller From Helium-Recycle Compressor, Showing Damage to Blades.

The relatively long period of successful operation at 1,000° F. indicated that the second failure may have been caused by creep of the type 304 stainless steel rotor. Type 304, selected for its excellent welding and machining properties, does not have exceptional creep properties, but calculations showed it to be adequate for 1,000° F. operation at the existing stress level. Later, however, it was learned that austenitic steels exposed to helium at high temperatures lose up to 30 percent in tensile strength.

After 265 hours of operation at temperatures of 700° to 900° F. the rotor "froze," marking the third time the compressor failed. Inspection revealed that:

1. The impeller shaft was bent;

2. The front compressor bearing had overheated and all lubricant was lost;

3. The outer races of the motor bearings were loose in their bushing inserts;

4. The screws securing the front motor bell to the motor frame were loose.

The following revisions were made to the compressor:

1. The type 304 stainless steel shaft was replaced with a shaft of type 316, which has better high-temperature creep strength, and was attached to the rotor with a threaded joint;

2. A backup nut was provided to prevent the impeller shaft-lock nut from loosening;

3. New compressor bearings were installed;

4. The compressor and motor assembly were doweled.

The revamped compressor ran for 800 hours with inlet helium temperatures of 750° to 950° F. This compressor was replaced with a new compressor with a rotor fabricated from Discaloy (13 percent chromium, 25 percent nickel, and 3 percent molybdenum), which has sufficient creep strength to be used in high-temperature helium at the existing stress level. In addition, a flanged joint was provided so that the machine could be more easily disassembled.

Helium-Purification System

Cylinder helium is relatively pure, but the recycled helium in the ISR loop contains oxygen, water vapor, carbon monoxide, and carbon dioxide. Evidently, these impurities are occluded in the graphite and ceramic materials comprising the simulated fuel elements and the reactor core, and are driven out at high temperatures and carried along by the helium. Oxygen, water, and carbon dioxide react with carbon to form carbon monoxide, and hydrogen tends to react with carbon to form methane--reactions that consume carbon. Therefore, because both fuel elements and moderators in a high-temperature process heat reactor probably will be carbon in the form of graphite, it is imperative that these gaseous impurities be continuously removed.

A 1-percent side stream of the helium is continuously passed through a purification system to remove occluded gases and reaction products. As originally installed, the gas cleanup system consisted of (1) a vessel containing hot copper turnings, (2) a water-cooled condenser, and (3) a phosphorous pentoxide drying unit. This arrangement was designed so that free oxygen in the loop would combine with the copper, hydrogen would react with oxygen to form water vapor--most of which will come out in the condenser--and the final traces of water would react with the phosphorous pentoxide to form phosphoric acid.

Concentration of water vapor inside the loop was much higher than anticipated, however, indicating that the original purification system was inadequat

Furthermore, during initial operation large amounts of carbon monoxide and hydrogen were generated--the concentration of each reaching approximately 25 percent--indicating that the carbon reacted with considerably more water vapor than free oxygen. A carbon loss of 10 pounds, 3 ounces necessitated replacing the spheres in the bed and required alterations to the purification train to eliminate further losses of this magnitude.

As shown in the redesigned purification system, figure 10, two freon-cooled condensers in series remove moisture from the recycled helium. Water is frozen out of the gas stream, and each day the condensers are isolated and thawed; when the accumulation of water becomes negligible (less than 1 cc. in 24 hours), use of the condensers is discontinued. To remove as much water vapor as possible before startup, a Stokes vacuum pump with a capacity of 100 std. c.f.m. of free air evacuates the system to less than 1 mm. mercury.

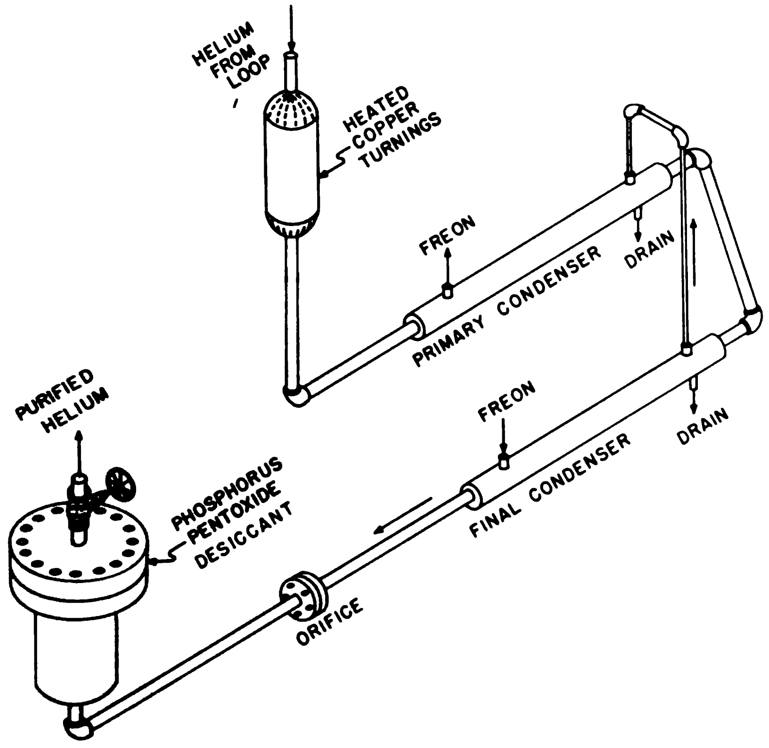

FIGURE 10. - Helium-Purification System for Induction-Heated Simulated Nuclear Reactor.

The revised purification system operated satisfactorily, and carbon loss has been reduced enough to allow continuous operation for relatively long periods.

Valves and Flanges

The bellows-seal valves (fig. 11) functioned satisfactorily, except that one 2-inch valve leaked at the body flange owing to deterioration of the Teflon gasket at 1,000° F. The Teflon gaskets were replaced with impregnated asbestos gaskets that have permitted satisfactory operation. The 1-inch and 1/2-inch valves have welded bellows and require no gaskets.

The octagonal ring-joint flanges with type 304 stainless steel rings performed satisfactorily in the 1,000° F. circuit; no leakage was evident when the flanges were tested with the Veeco Mass Spectrometer Leak Tester, Model MS-9A.

Helium Leakage

The system was pressurized to 375 p.s.i.g. (1-1/2 times operating pressure) and checked with the helium leak detector, which detects helium concentrations as low as 1 part in 10 million. All flanges in the system were tight

Original from THE OHIO STATE UNIVERSITY

except the flanges on the ISR pressure vessel, which, as previously indicated, were slightly warped when the vessel was heat-treated.

Of the 348 welds in the helium loop as originally constructed, varying in size from the weld around the 30-inch flanges of the pressure vessel to welds on 1/4-inch instrument connections, only 8 showed leakage during the detector test. These were cut out and rewelded, and tested leaktight.

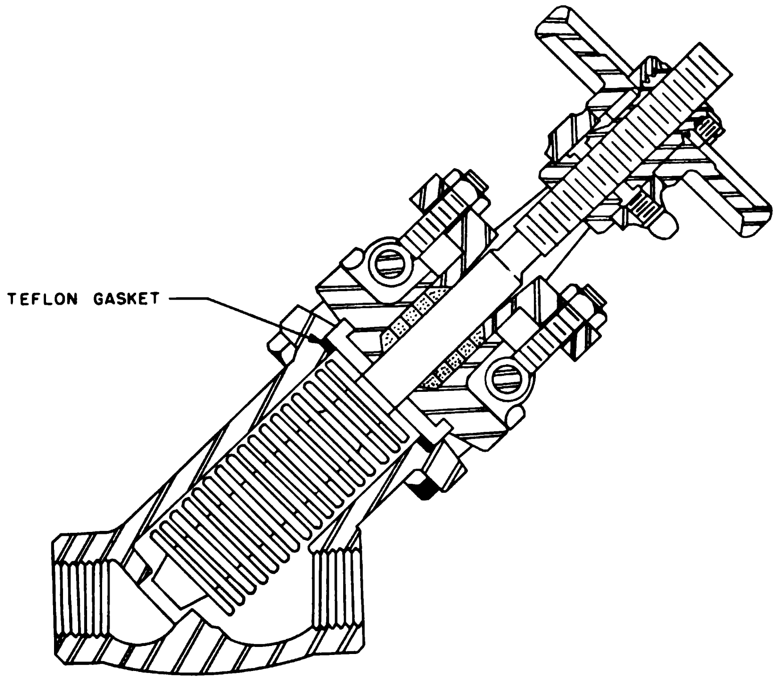

FIGURE 11. - Bellows-Seal Valve for Helium at 300 p.s.i.g. and 1,000° F.

When the system was pressurized to 300 p.s.i.g., helium leakage was 4 std. c.f.h. or 0.8 percent per hour, most of it from the 30-inch flange on the pressure vessel and the electrical connections of the conduit carrying the 9,600-cycle current into the reactor.

Seal welding rendered the distorted 30-inch flange leaktight, and the thermocouple outlets also tested leaktight after the soapstone packings were replaced with Teflon.

Since these modifications the system has been operated at 2,600° F. and 100 p.s.i.g. Most of the leakage, 0.675 std. c.f.h., occurred at the electrical connection.

CONCLUSIONS

A helium-recycle system with gas temperatures of 2,300° to 2,500° F. and a static pressure of 250 p.s.i.g. appears feasible. However, further development is required on high-temperature heat exchangers and recycle compressors.

Although operable pilot-scale equipment has been demonstrated, problems circumvented on this scale must be solved before larger systems can be built. In large heat exchangers, the problems of leakage and thermal expansion will be much greater. While compressors can be designed for the required conditions of head and flow, helium leakage is a problem. "Canning" can be used advantageously for small machines, but gas-lubricated bearings are necessary to avoid contamination of the helium by lubricants. Large compressors will require gastight shaft seals.

Contamination of the recycled helium by gases occluded in the materials in the loop has been a greater problem than originally contemplated. Water vapor, which is present in concentrations exceeding that of any other impurity, attacks unclad carbon or graphite in the high-temperature section of the loop. Further work with insulating materials is required.

Leakage of helium in a high-temperature loop can be reduced below 1 std. c.f.h. Ring-joint gaskets have been demonstrated as leaktight for helium at 1,000° F. and 250 p.s.i.g. No difficulty was experienced in obtaining leakproof welds in type 304 stainless steel at these conditions.

U.S. GOVERNMENT PRINTING OFFICE : 1960 O—562847